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BALLET: BALloon Locomotion for Extreme Terrain

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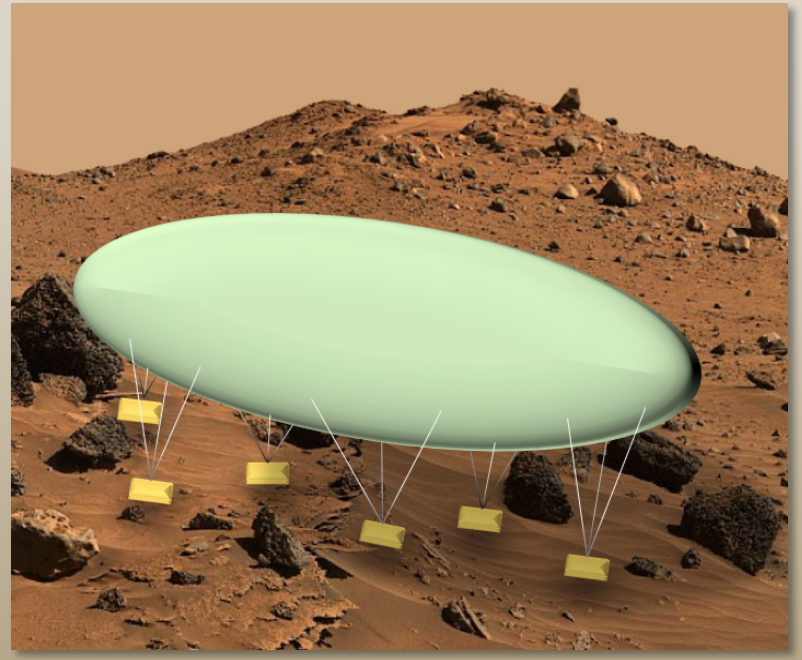
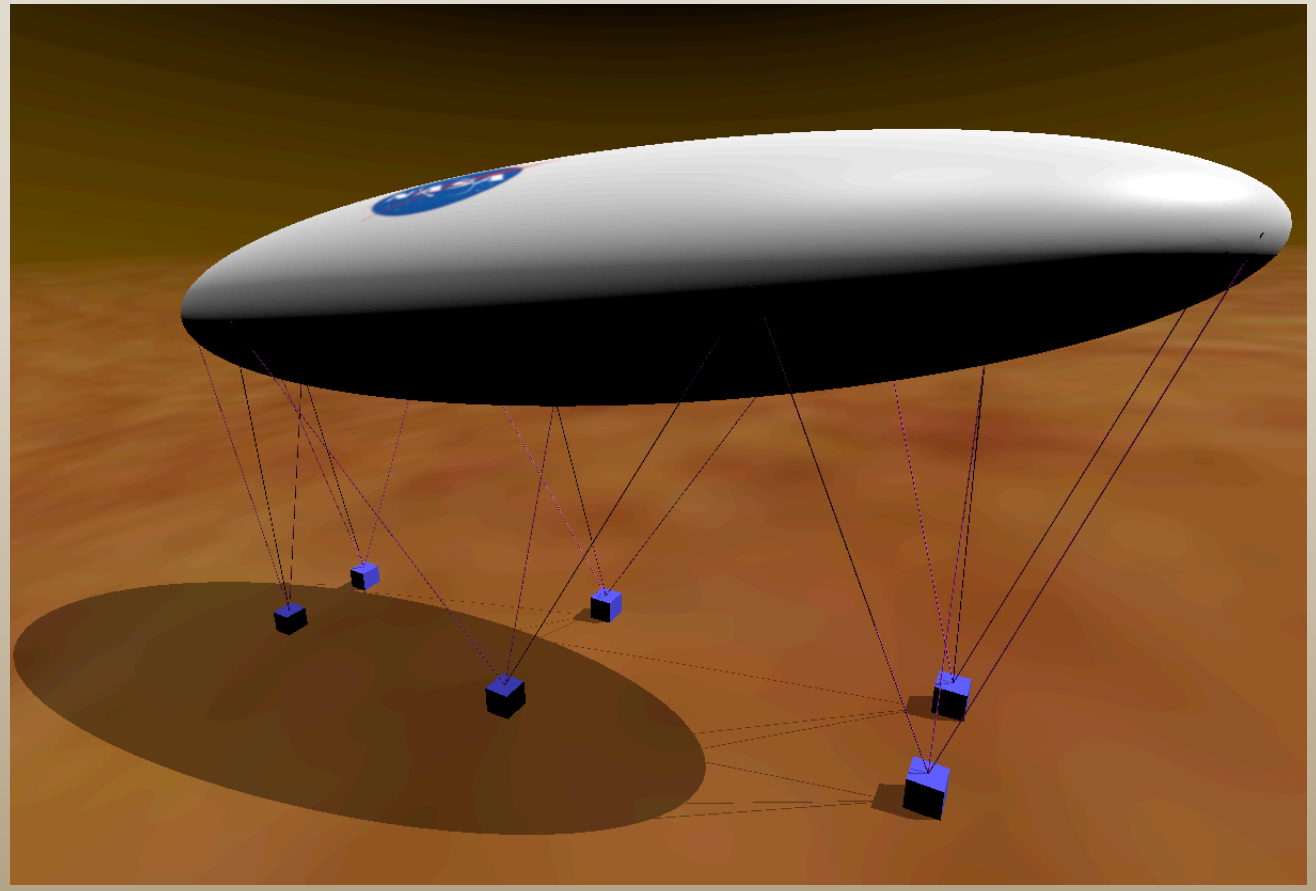


Concept Overview

- BALLET offers a new approach for traverse over extreme terrain on planetary surfaces with atmospheres
- Balloon platform with 6 suspended modules, each containing a science payload that also serves as a foot
- Each foot is suspended by 3 cables that are used to control the placement of the foot on the ground
- Only 1-2 payload(s) raised at a time to take a step; remaining feet keep the balloon anchored to the surface
- With all feet on the ground, the balloon is moved by changing cable lengths
- Feet are moved in sequence to locomote over the surface
- The platform is highly stable because its center of gravity is at ground level
- Images from cameras on the balloon are used to map and locate foot placement and for navigation



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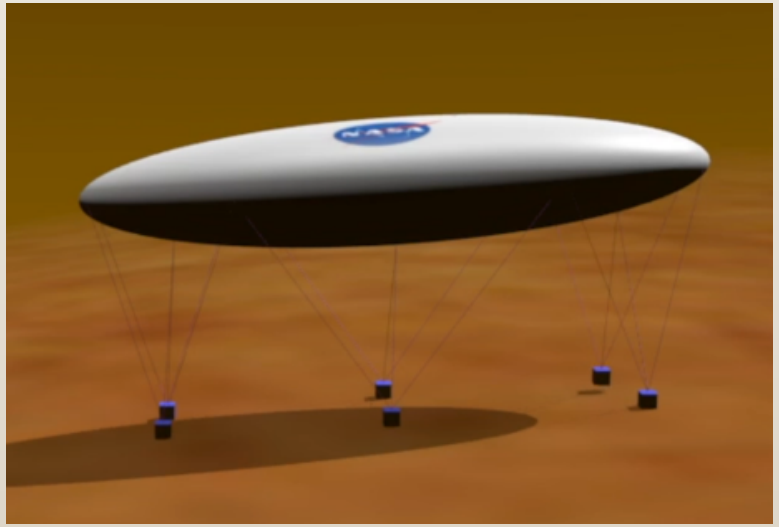
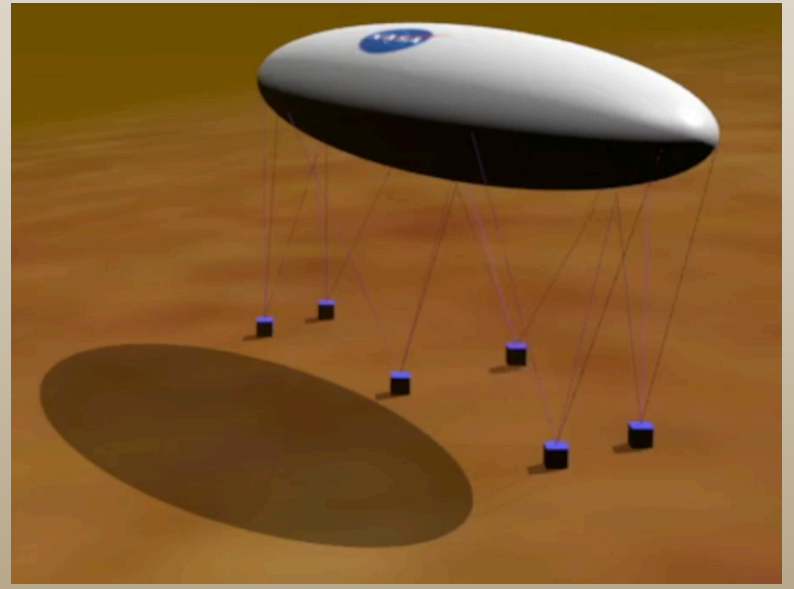
Novelty and Innovation

- Enables in-situ science operations at scientifically exciting but previously inaccessible locations
- Achieves its benefits through several innovations:
  - Use of a balloon for buoyancy and as a platform for locomotion
  - Limbs composed of cables in tension with significantly less mass than legs composed of links in compression
  - Partitioning the payload into six modular elements and lifting of only one or two at a time to significantly reduce the needed buoyancy and balloon size
  - Placement of the science payload in the feet keeping the center of gravity very low and the platform highly stable





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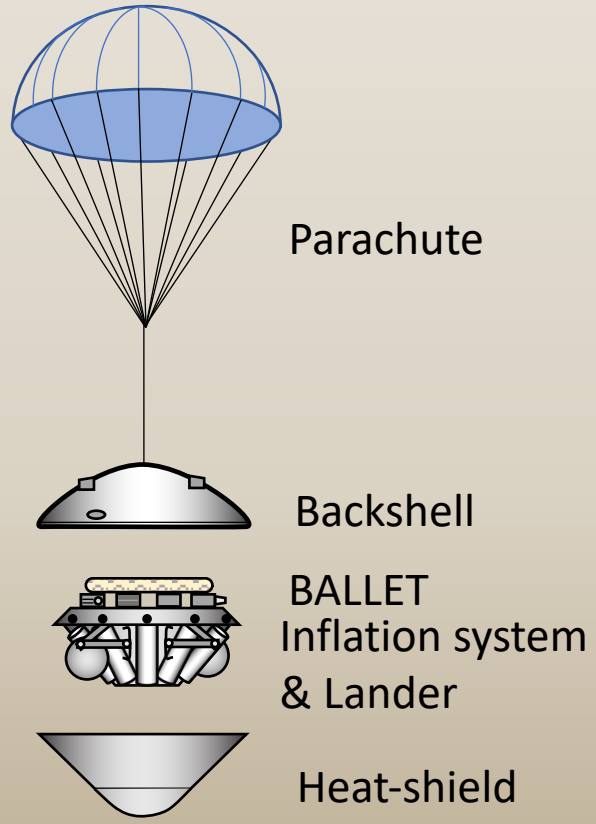
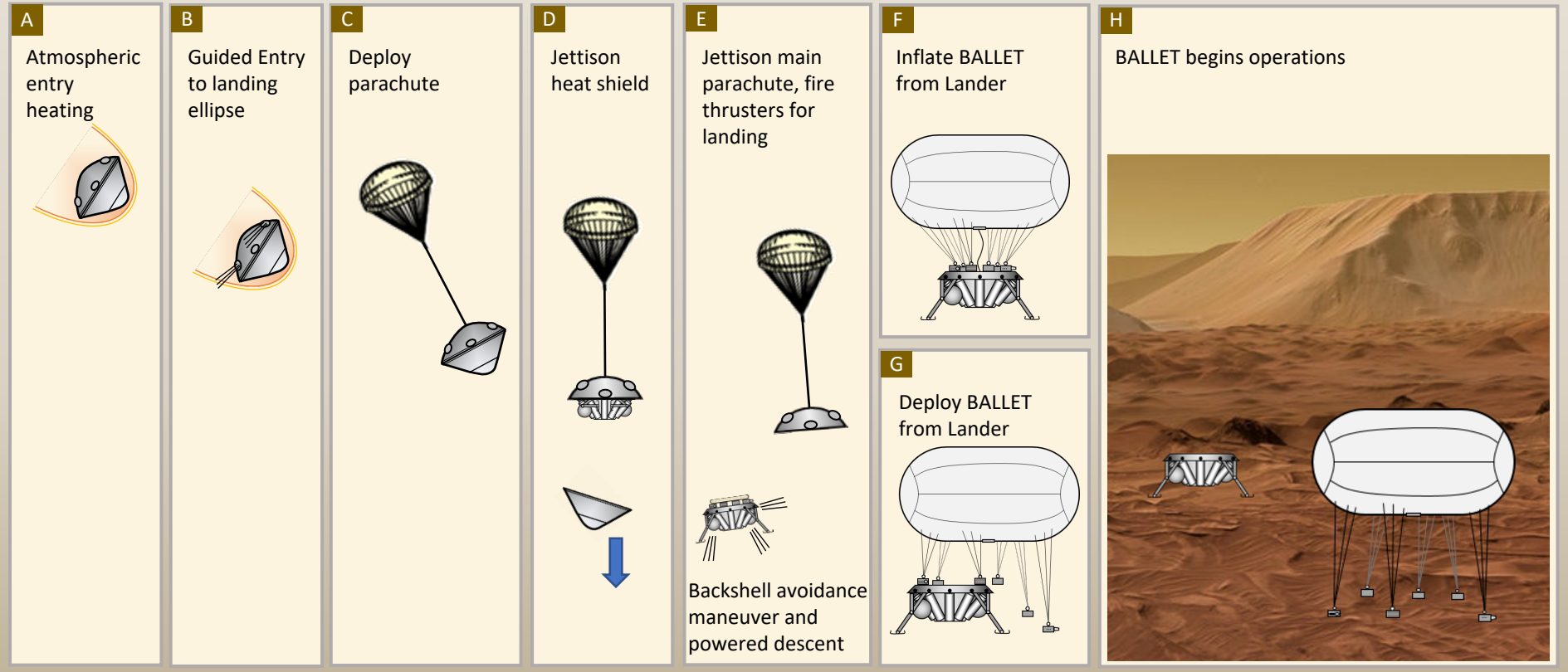
Mission Context and Deployment





- The deployment sequence upon entry as shown here.

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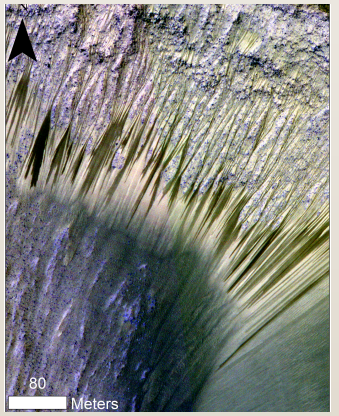
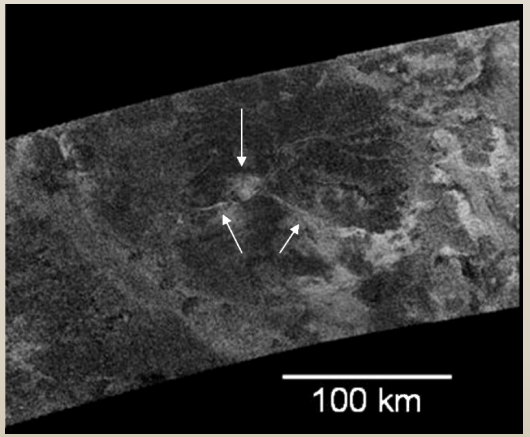
Proposed Science Objectives

- **Explore Mars Recurring Slope Lineae (RSL)**
  - Seasonal events comprised of either liquid brine flows or dry granular avalanches
  - Targets of investigations for habitability and/or astrobiology
  - Requires access to terrain with slopes of 27-40 degrees (the steepest slope attempted by a rover on Mars was 32 degrees)
- **Explore Titan Cryovolcanic Flows**
  - Some evidence, but not yet confirmed of eruption of volatiles (water, ammonia, methane) from Titan subsurface
- **Explore Titan Lake Shorelines**
  - Confirmed presence of liquid hydrocarbon lakes on Titan, but the composition and their shorelines is still unknown.
- **Meet engineering constraints**
  - Science instruments be distributed among feet and meet mass and size restrictions

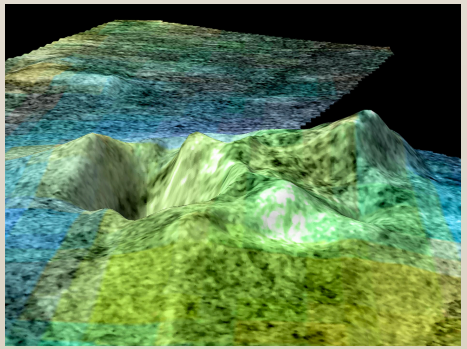


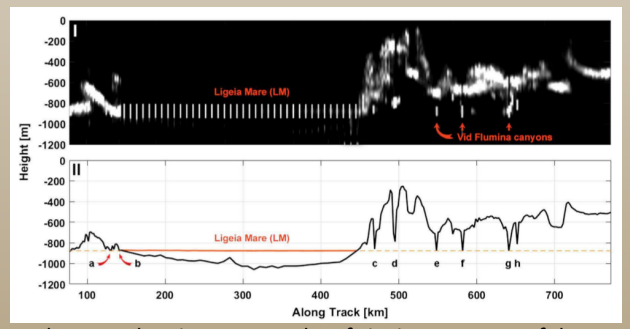
RSL observed by HiRISE emanating from Palikir crater during southern summer. Credit: NASA/JPL.



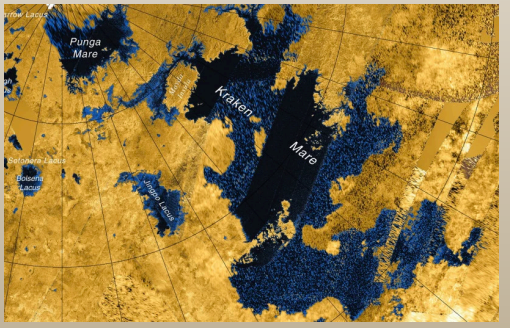
Ganesa Macula, a putative cryovolcanic dome. Arrows indicate central caldera and channels (Lopes et al. 2007).

Topographic computer model of Sotra Patera, a putative cryovolcano on Titan. Credit: NASA/JPL-Caltech/USGS/Univ. of Arizona.





Radargram showing topography of Ligeia Mare, one of the northern lakes of Titan (Poggiali et al. 2016).



Colorized mosaic of Cassini radar images of the northern lakes of Titan. Credit: NASA/JPL-Caltech/ASI/USGS.

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Proposed Science Payload

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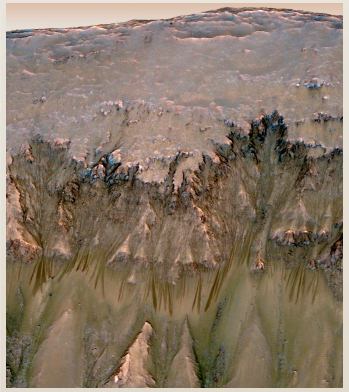
Mars Recurring Slope Lineae Mission

Science Objective	Example Payload Element	Mass (kg)
Determine if RSLs are formed by liquid water or dry grains	Relative humidity sensor [REMS-H on MSL]	<<1[a]
	pH/eH/conductivity [TECP on Phoenix robotic arm]	<1
	Ion selective electrodes [WCL on Phoenix MECA]	<8.5[b]
Search for evidence of habitability/life	Organic microfluidics detector [Urey on ExoMars[c]]	4.4[c]

[a] Entire REMS met package (including sensors for wind, pressure, temperature and UV) was 1.243 kg.
[b] Includes components such as optical and atomic force microscopes which would not be required for BALLET.
[c] Proposed but ultimately descoped. Mass estimate is from 2008, probably out-of-date for any new prototype.



Credit: NASA/JPL

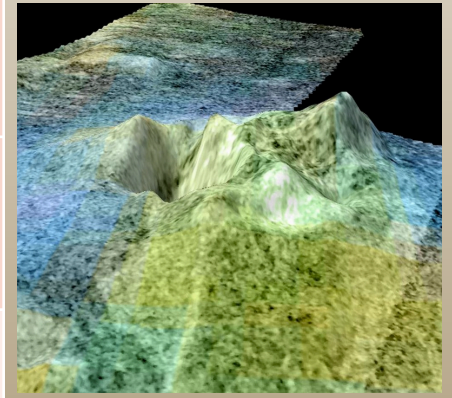
Titan Lake Shorelines Mission

Science Objective	Example Payload Element	Mass (kg)
Determine lake composition (both hydrocarbons and dissolve components)	Immersion probes – UV/vis for dissolved aromatics, NIR for methane/ethane/propane ratio [FOCALS prototype]	<1
Determine composition of the shoreline	Raman spectrometer [SHERLOC on Mars 2020]	1.6
	Laser Desorption Ionization MS [MOMA on ExoMars]	1.6
Identify lake dynamics (wave activity, bubbles due to exsolvation, etc.)	Context camera [MAHLI on MSL]	<0.5
	Bubble size/distribution probe [EnviroCam prototype]	<<1
	Meteorology package [SSP of Huygens probe]	4.2*

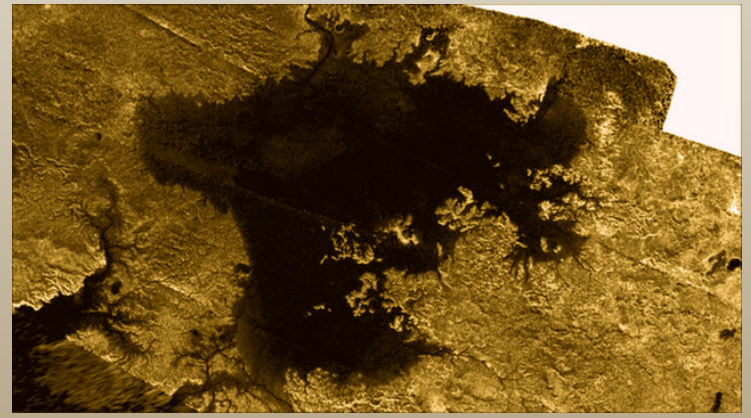
* The Surface Science Package includes sensors for permittivity and acoustic properties which will not be required. This instrument suite could also be split into multiple packages to meet mass constraints.

Titan Cryovolcanic Flows Mission

Science Objective	Example Payload Element	Mass (kg)
Determine whether organics have been altered by liquid water (i.e., search for amino acids and other products of hydrolysis or oxidation).	Laser desorption ionization mass spectrometer [MOMA on ExoMars]	1.6
Determine the age of the cryovolcanic flow via isotopic ratios ($^{13}C/^{12}C$, D/H).		
By composition of the cryovolcanic flow, determine: (1) if it is sourced from the liquid water ocean and, if so, (2) the composition of the ocean.	Raman spectrometer [SHERLOC on Mars 2020]	1.6
Assess whether cryovolcanic flow composition and morphology varies over the surface of the flow.	Context camera [Mastcam-34 on MSL]	0.8
	NIR imaging spectrometer [UCIS prototype]	1.5



Credit: NASA/JPL-Caltech/USGS/Univ. of Arizona.



Credit: NASA/JPL-Caltech/ASI/Cornell

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Force & Moment Balance Analysis

- For a specified balloon size, the feet must be massive enough to anchor the balloon but light enough to be lifted
- Each limb is modeled as a single cable hanging in the center of the three connection points
- When lifting one or more feet for locomotion, the tensions are no longer equal. Solving for the tensions is an underdetermined problem.

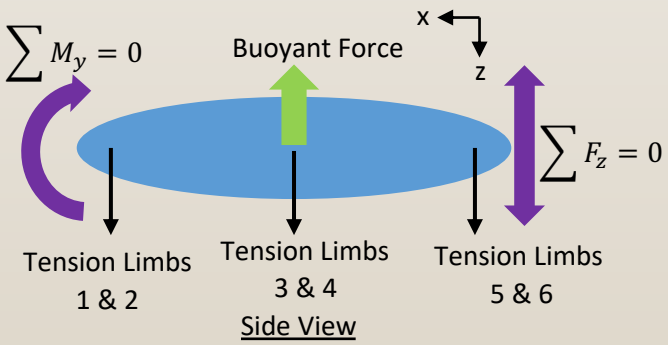
Equations

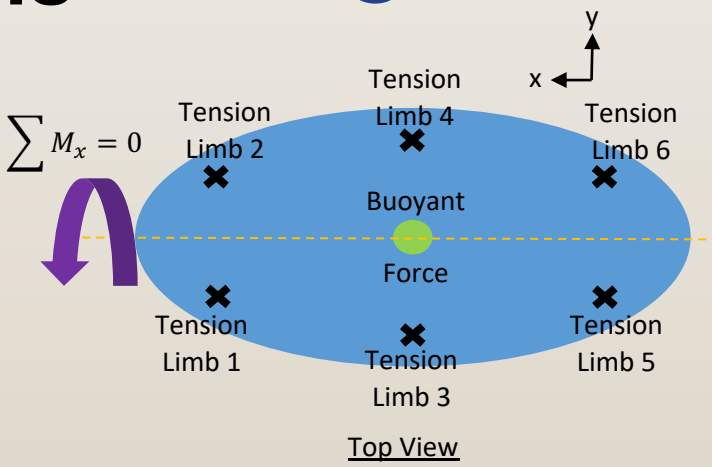
$$\sum M_y = 0, \sum M_x = 0, \sum F_z = 0$$

Unknowns

$T_n > 0$ Tension for all limbs n that are not being lifted

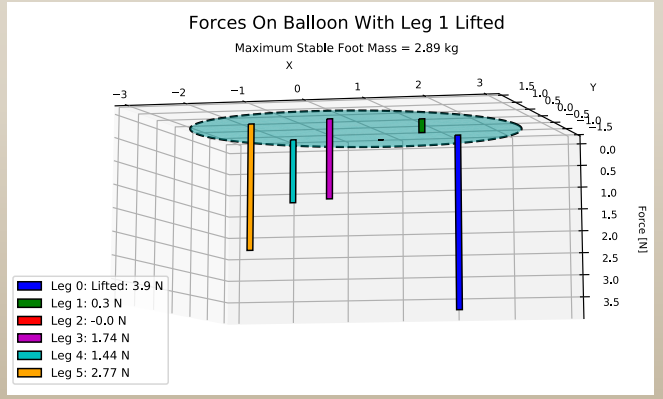
- There are more unknowns than equations
- The least squares method was used to find the tensions in cables when specific legs are lifted with a known mass attached to the foot
- Optimization was performed to find the maximum foot mass that still resulted in a stable balloon.

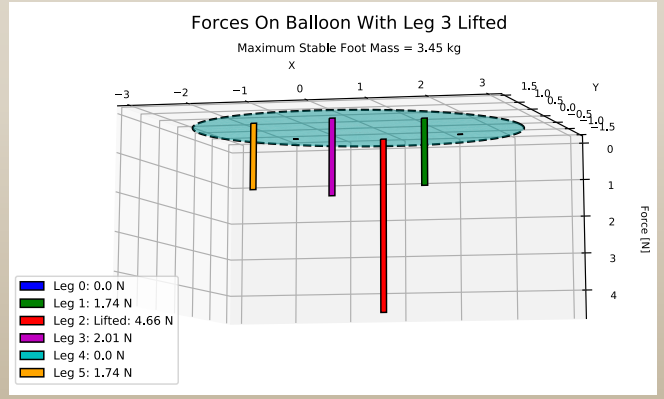




This analysis was performed for an 11.534 m³ balloon on Titan

First, look at lifting a single leg:





The above figures show the magnitude of the tension in each cable of the balloon at the maximum stable foot mass when lifting the specified leg.

Result: The foot mass for a balloon on Titan that lifts one leg at a time must be greater than 1.25 kg and less than 2.89 kg to remain stable

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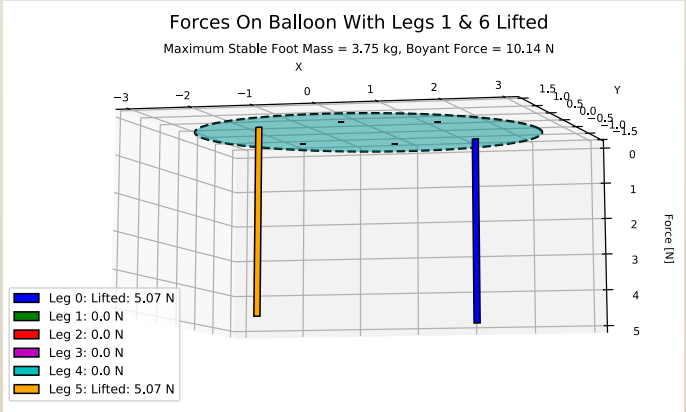
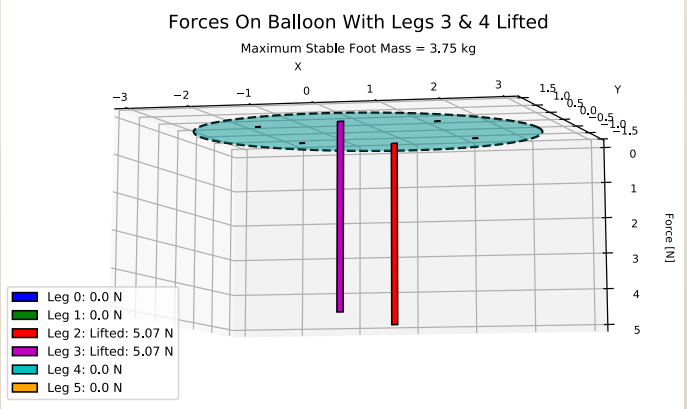
Force & Moment Balance Analysis

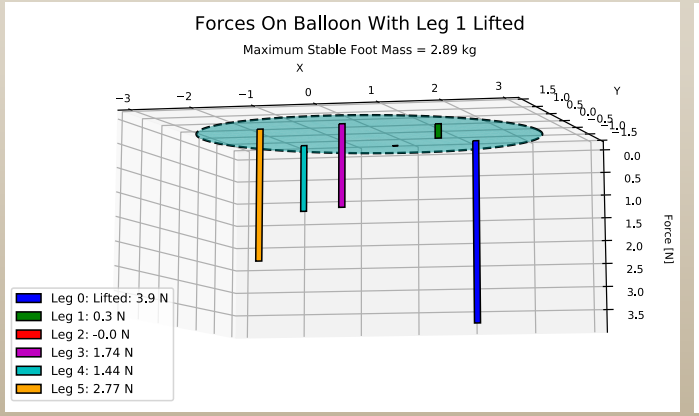
- Next, look at lifting two legs on the same balloon
- Result: The foot mass for a balloon on Titan that lifts two legs at a time must be greater than 1.25 kg and less than 3.75 kg to remain stable
- Lifting opposite legs simultaneously negates the moment that would otherwise have to be counteracted by other cables. This allows for the feet to have greater mass than when lifting one leg at a time, while maintaining high stability

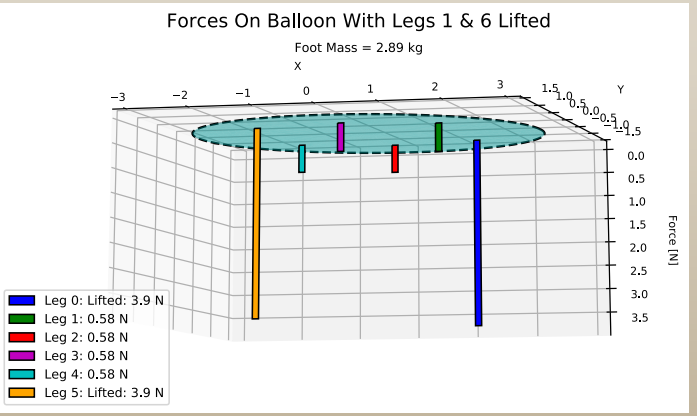




The above figures show the magnitude of the tension in each cable of the balloon at the maximum stable foot mass when lifting the specified legs.

- Using a mass of 2.89 kg, it can be clearly seen why lifting two feet is more stable than lifting one:
- Lifting two legs, at the stable foot mass found for a single lifted leg, results in all cables maintaining tension. When a single leg is lifted, one cable loses tension entirely, demonstrating poor stability





The above figures show the magnitude of the tension in each cable of the balloon at the maximum stable foot mass when lifting one foot.

Locomotion lifting two opposite legs simultaneously will result in a more stable balloon, and allow for more science instruments to be carried

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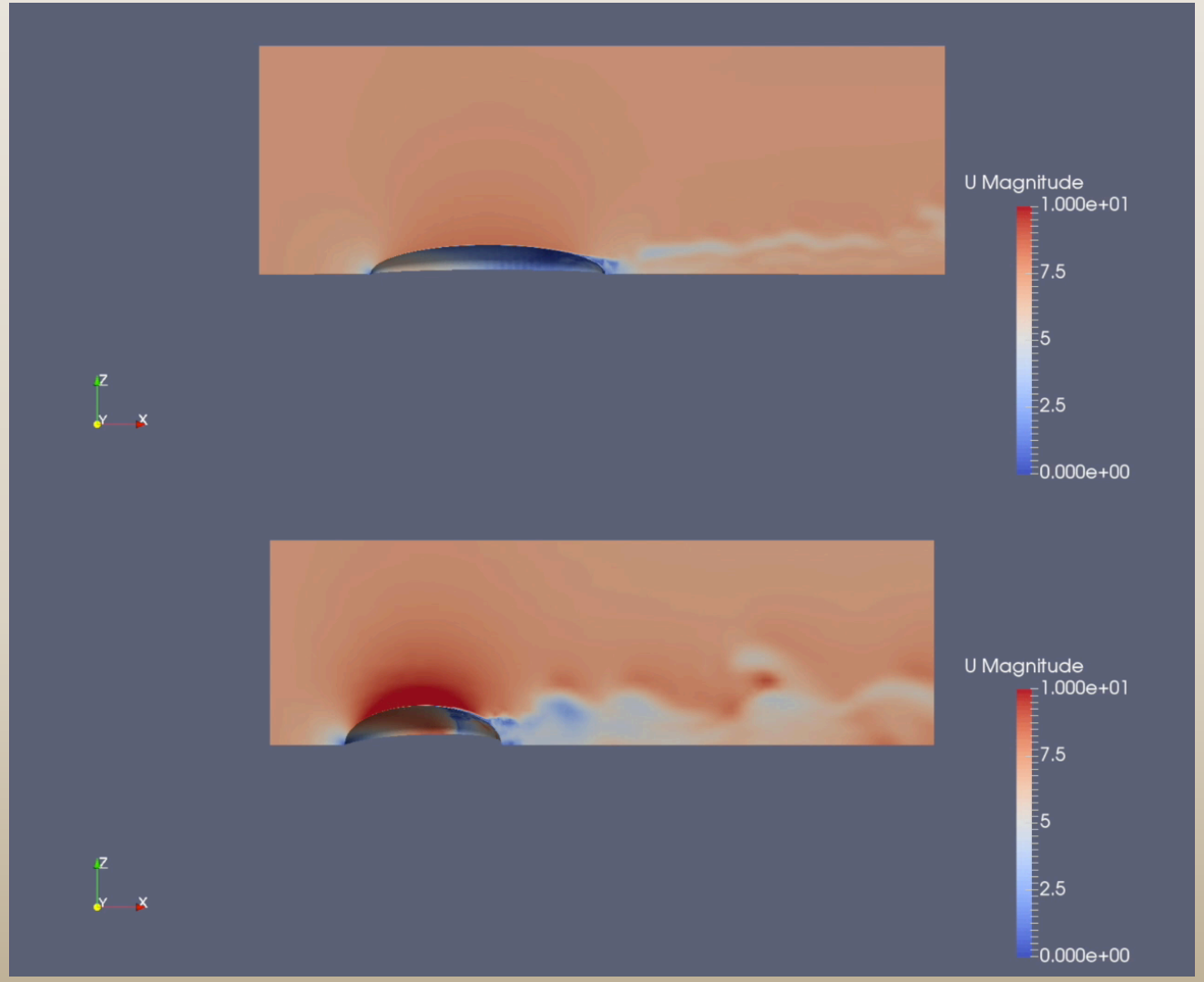
Aerodynamic Forces

- Aerodynamic forces can have great effect on balloon stability. High drag can cause BALLET's feet to slip, or change its stability. High lift can pull the BALLET into the air, or push the balloon into the ground.

- OpenFOAM was used to simulate flow over the ellipsoidal balloon with air properties expected to be found on Mars, Earth, and Titan. Lift and drag were recorded at an angle of attack of 0° and 10°.

- Result: Aerodynamic forces will be an issue for a mission to Mars, with expected lift and drag forces exceeding the weight of the balloon. Titan offers the best scenario with low wind speeds and a small required balloon size.

- In all cases, in order to achieve the lowest possible aerodynamic forces, BALLET should align its long axis with the wind direction. This is true for both lift and drag



Earth air flowing over the balloon at 7 m/s. The top video shows the case of BALLET facing into the wind. The bottom video shows BALLET experiencing transverse winds.

Facing into the wind minimizes the aerodynamic forces experienced by BALLET

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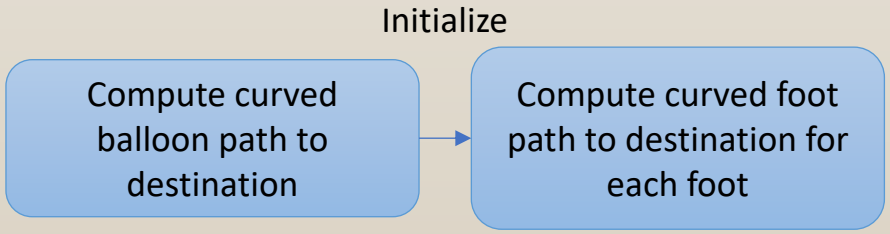
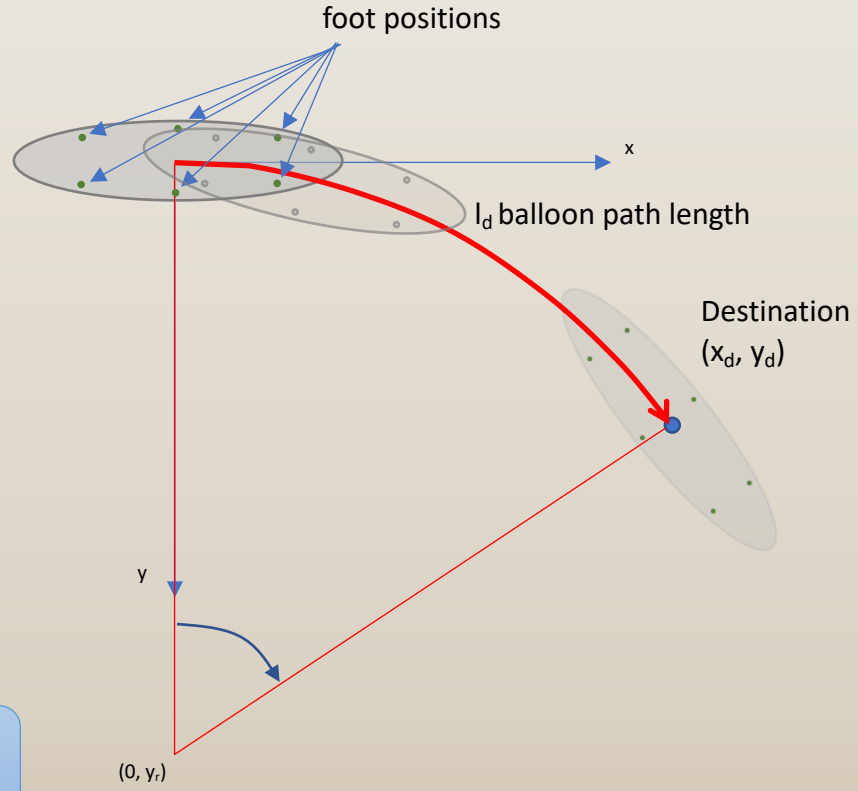
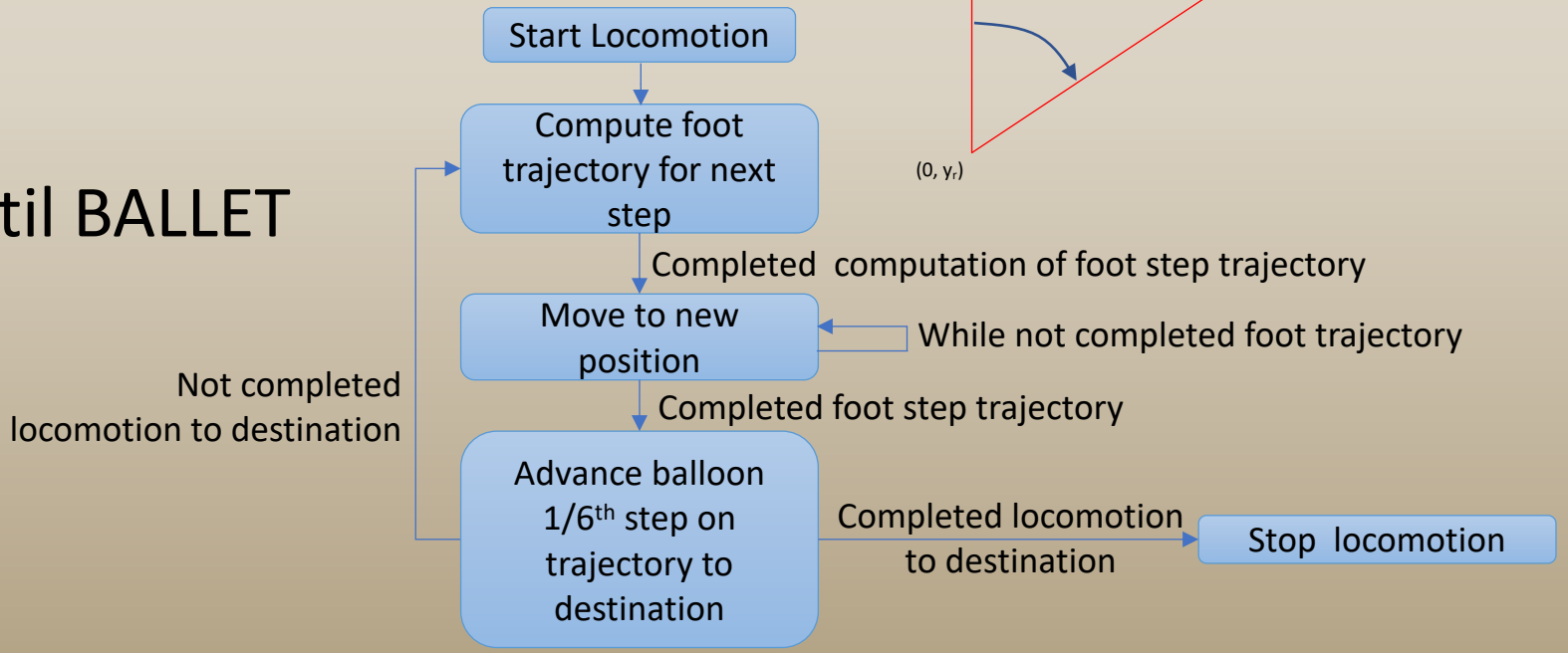
Mobility

- Motion is highly choreographed
- Find the curved path to the destination





- Execute locomotion until BALLET reaches destination



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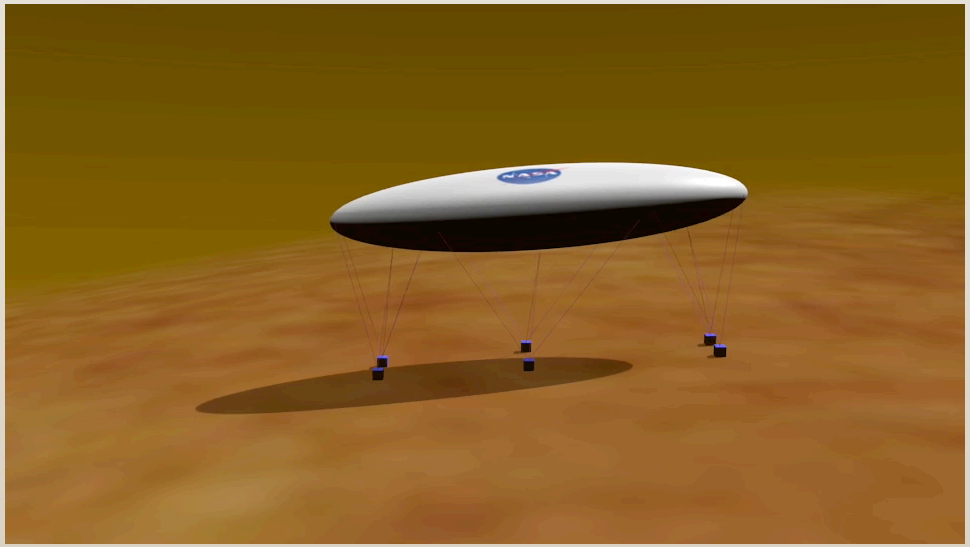
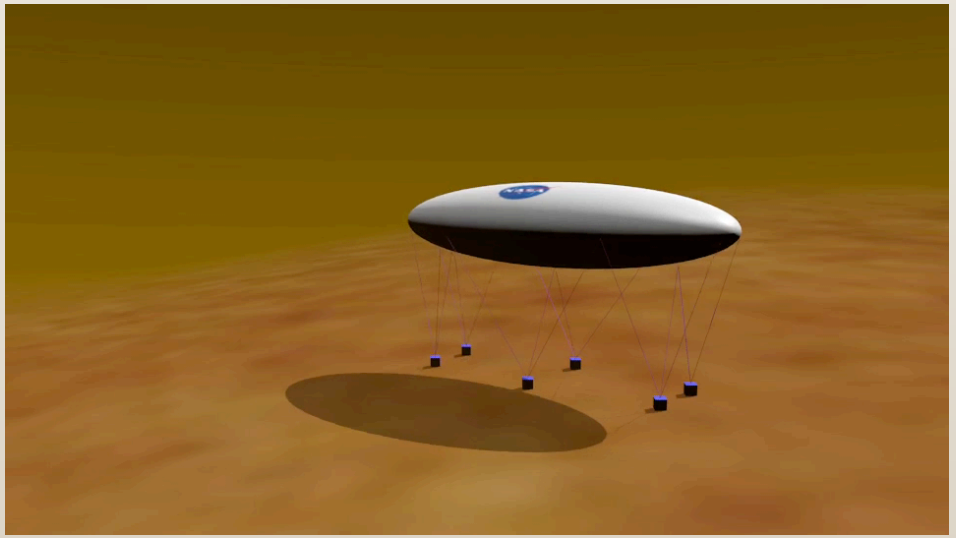
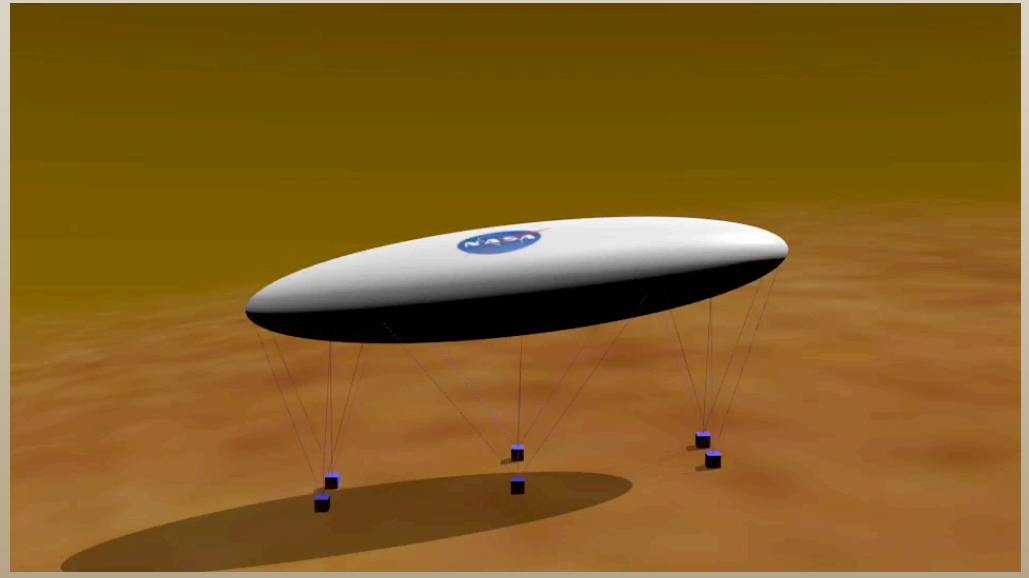
Mobility



Single-step Straight Line Motion



Curved Path Motion



Two-Step Locomotion

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